Comments on
Edouard Bard and Timothy J. Heaton (B&H)
On the tuning of plateaus in atmospheric and oceanic ^{14}C records to derive calendar chronologies of deep-sea cores and records of ^{14}C marine reservoir age changes.
Climate of the Past. Discussions

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In the fall 2019, Edouard Bard and Tim Heaton (B&H) got access to the discussion version (opened in CPD at 25-10-2019) of our paper "Plateaus and jumps in the atmospheric radiocarbon record – Potential origin and value as global age markers for glacial-to-deglacial paleoceanography, a synthesis" (Sarnthein et al., Clim. Past 16, 2020 (SA2020)). A letter to the Editor of CPD on 31-01-2020 stated they had written an extended comment to the paper but had submitted it as a research paper since it "*includes substantial material of broad interest to the community using radiocarbon in marine sediments for geochronology and paleoceanography*". This comment is now subject of our discussion. Its aim is to demonstrate that Plateau Tuning (PT) is fraught with problems and should not be used.

We thank B&H for the time and efforts they spent formulating the problems they see with the technique of ^{14}C plateau tuning. Their detailed arguments and reasoning extend far down to basic processes that may control an atmospheric and sedimentary ^{14}C record and thereby provide a base for a factual discussion of PT. Both basics and details are important when evaluating potential major-to-minor pitfalls of PT but can rarely be discussed at meetings or workshops (B&H *lines 65-69*). As stated in their letter the paper 'includes substantial material of broad interest' and many of their potential pitfalls are worth considering. Our response may help to clear various misconceptions and further explain crucial aspects of the PT method. This is important since all of us aim to find the best-possible techniques to generate proper age control of ocean sediment records and to make an optimum use of the wealth of environmental information they contain. Below we summarize two points where B&H misconstrued PT and we advocate a different conclusion from their Fig. 3 , 5, and 6. Then we address their specific chapters and text.

Summary

Many of the 17 objections raised by B&H are based on two simple points:

(1) *The difficulty of reliably identifying a single ^{14}C-concentration plateau in a noisy ^{14}C sediment record and then finding its correct partner in the noisy record of atmospheric ^{14}C concentrations*

This is the subject of eight objections (2.1; 2.2; 2.5; 2.6; 3.3; 3.4 straight and part of 2.3 and 3.1). These objections are based on *lines 40-41*, the first lines of the B&H Introduction: In line 40 the term *'a suite of'* is missing between '*tuning*'and '*hypothesized*' and in line 41 *'those that*' should be replaced by '*a suite of plateaus'*.

The problem of how to identify a plateau has been extensively considered in the development of PT. Sarnthein et al., 2007 clearly mention they '*identified a reference suite of prominent atmospheric ^{14}C "plateaus"* ', based at the time on Cariaco ODP 1002 and on U/Th dated corals and Bahama speleothem, and the identification of *'analogous series of ^{14}C plateaus in several other marine sediment cores …*'. This emphasis on suites of plateaus and suites of tie-points has been part of every PT paper including SA 2020, discussed by B&H. As B&H point out: Identifying a single plateau is very hard. Further details on meeting this set of questions are given in the companion response text of Sarnthein & Grootes (S&G).

(2) The focus on ^{14}C concentration changes in the surface ocean (pla = planktic ^{14}C concentration) instead of on marine reservoir age (MRA = pla- Atm, where Atm is the contemporaneous atmospheric ^{14}C concentration).

This leads to objections 2.3; 2.7; 2.8; 3.1 and 3.2 that basically repeats 2.3.

In a simple carbon cycle box-model (e.g. Siegenthaler et al., 1980) with a deep ocean that contains about 60 times more carbon and 50 times more radiocarbon than the atmosphere, most of the variability in ^{14}C concentration will be in the atmosphere and in its closely-connected thin ocean-atmosphere exchange layer. The focus of B&H on the surface ocean is logical, because it is easily accessible and its plankton provides our paleoenvironmental record, but MRA is the difference in ^{14}C concentration between atmosphere and surface ocean (*pla-Atm*). B&H use the Bard et al., 1997, 12-box model to calculate an attenuated and somewhat delayed response of the surface ocean to, especially rapid, atmospheric ^{14}C changes. This leads them to reject the PT derived MRA changes as "too large, too frequent, too abrupt". Their modelling addresses, however, only one facet of MRA, and a strongly attenuated *pla* signal will generate an MRA (= *pla-Atm*) signal with little attenuation. This is borne out by the effects on MRA of the ^{14}C bomb spike and Miyake events mentioned in their text. A box model, moreover, does not consider local variations in near-surface ocean mixing and ocean-atmosphere exchange, that can lead locally to large and rapid changes in *pla* and thus MRA for an unchanged atmosphere.

Fig. 3a shows the translation of the PT suite of plateaus, defined by SA2020, in the ^{14}C-age/ calendar-age domain, into the $\Delta^{14}C$/calendar age domain and compares the translated plateau step curve with the Bayesian-spline generated Suigetsu atmospheric record. The statistically sound zig-zags of the Bayesian Suigetsu curve reveal a generally satisfactory agreement with the (green) plateaus (sections of (faster) decreasing $\Delta^{14}C$ vs. decreasing cal. age) and jumps (sections of slower decrease or increase), despite the fact that the plateaus defined by Sarnthein et al. (2015 and 2020) were based on the 2012 Suigetsu data and did not consider the most recent age corrections of Bronk Ramsey et al., (2020). The zig-zag curve does not pin the plateau slope to zero and offers another look at the position of inflection points, so far defined by the beginning and end of zero-slope plateaus. This will be further explored for PT.

The modelling exercise of 3.6 and 3.7 demonstrates how the statistical scatter of sampling and imperfect measurements may distort and mask underlying real signals. Yet, contrary to the stated conclusion, it offers hope in showing that at least two out of the three ‘plateau’ features of the underlying short record can indeed be found in the modelled examples. It also makes a clear point that such identification of the ‘true’ fine structure of a ^{14}C record is a serious research project requiring consideration of a broad range of conventional age tie points and oceanographic information and a long sequence of plateaus in order to produce reliable results. And, even then, it still needs to be checked against other independent records.

In the following we first comment on B&H Chapter 1. and then address the objections of Chapters 2 and 3.

1/ Introduction

Line 40-41: A small but crucial element is missing in the introduction of PT. The technique tunes **a suite** of ^{14}C age plateaus in a sediment record against **a suite** of plateaus defined in the atmosphere (as represented by the Suigetsu record). Such a suite covers usually 5000 to 10 000 years and is crucially needed to define a proper match and deal with local disturbances that may distort, eliminate, or mimic single plateaus.

Line 58*:* contains the quote '*ocean models still poorly reproduce" their reconstruction …"'*

The quote is correct but the paragraph misrepresents the SA2020 paper. Ventilation ages are obtained via the difference in ^{14}C concentration between benthic foraminifera and the atmosphere (*Be-Atm*). The deep ocean contains 60 times more C and 50 times more ^{14}C than the atmosphere, so in a carbon cycle mass balance model the ^{14}C concentration in the atmosphere fluctuates about 50 times more than in the deep ocean. Most of the variability in *Be-Atm* will thus be in the atmosphere. The changes in *Be* related to the deep ocean circulation and the release or drawdown of CO_2 will not be as large as the ventilation age variability appears to suggest. Core specific results often deviate from the predictions of global- or basin-wide ocean models, but this is often not due to bad data or a bad model but rather to a model not tuned to the specific core site conditions. One may say that progress in model development is prompted by boundary conditions and results not properly covered by existing models (Lohmann et al., 2020).

Lines 64-65: Umling and Thunell (2017) show in their Fig. 4 a close agreement between time scales obtained by tuning to Greenland ice cores, Hulu speleothems and ^{14}C plateaus using PT. Discussed in 2.4 *lines 214-223*

Line 72: *'the compiled records based on PT leads to perplexing outcomes (no coherence with either production changes or with ocean modelling results).'*

The wording is suggestive and misleading. Chances are small for finding clear correlations between ^{14}C fluctuations and ^{14}C production (except for Laschamp and Mono Lake) and/or ocean circulation/climate. A few correlations appear to be emerging, but we are still far away from coherence in the poorly known and highly variable deglacial.

A more neutral formulation could have been: '*The compiled records do not yet allow a clear attribution of the observed ^{14}C variations to ^{14}C production or carbon cycle changes'*

as pointed out by the authors themselves.

2/ Paleoclimatic and paleoceanographic perspective

2.1 "*Non-laminated ocean sediments are not suitable for wiggle matching*".

The base for this objection lies in the first introductory sentence (*lines 40-41*). PT uses indeed wiggle matching in a non-laminated sediment. The pattern of yearly ring widths of the tree is replaced by the pattern of ^{14}C concentration variations along a sediment core. Clearly a single plateau cannot yield a pattern. A suite of plateaus, correlated on the strength of its pattern, provides an 'elastic' time scale to the sediment depth record. The stratigraphic and sedimentological procedures and correlations used are presented in the answer to 2.1 by S&G and need not be repeated here.

2.2 '*PT assumes that the marine ^{14}C reservoir age is strictly constant during the age plateaus*' and since this cannot be, '*PT structures are severely under-constrained in ^{14}C and calendar ages*'

This objection has the same root as 2.1, namely that single plateaus are correlated. Indeed, single plateaus **can not** be reliably correlated, there are too many; the whole suite of plateaus is required! We use B&H Fig. 3 for a brief explanation of PT to counter the objections. Fig 3a shows Suigetsu ^{14}C concentrations as $\Delta^{14}C$ (a surrogate for the atmosphere), varying irregularly from 14 to 30 cal kyr BP on centennial time scales. These concentrations can be converted into a curve of apparent atmospheric ^{14}C ages against calendar age such as Fig.1 of B&H and of SA2020. The same can be done for ^{14}C concentrations of planktic carbonate in a sediment core plotted against depth. If an approximate time scale can be obtained for the sediment core based on conventional stratigraphic techniques and correlations (see also comment S&G), then an optimum match between local sediment and global atmosphere can be sought for the **full** ^{14}C age-pattern of irregularly alternating low slopes ('plateaus') and high slopes ('jumps').

Note: There is no assumption for MRA estimates! MRA = (*pla – Atm*) for each plateau pair.

The one crucial assumption is the one also used in IntCal to extract atmospheric ^{14}C concentrations from marine carbonate ^{14}C records, namely that there is a close correspondence between ^{14}C in the atmosphere and in the top layer of the local ocean.

The objections listed in *lines 100-105* are thus based on misunderstanding.

The problems listed in *lines 105-114* are real and are routinely encountered in PT. Abrupt changes in local oceanography or sediment disturbance can disturb, destroy, or mimic a plateau. Matching suites of plateaus will bring this out, although disturbance will make it more difficult to find the right match amongst alternative tuning possibilities. Plotting the planktic ^{14}C concentrations (or ages) against depth means the match will transfer the standard atmospheric time scale to the sediment core. This often reveals variable sedimentation rates. Checking whether those rates are physically realistic is one of PT's many quality controls, used to decide between alternative tunings. Matching the sediment record ^{14}C suite with the atmospheric master ^{14}C suite (Suigetsu) provides: 1). A series of time markers in the sediment at the inflection points of the wiggly curve (approximated by line segments as seen in Fig. 3a and Fig. 1) and 2). A series of difference values *(pla – Atm)* between the ^{14}C ages of matched plateaus in core and atmosphere, the estimates of MRA.

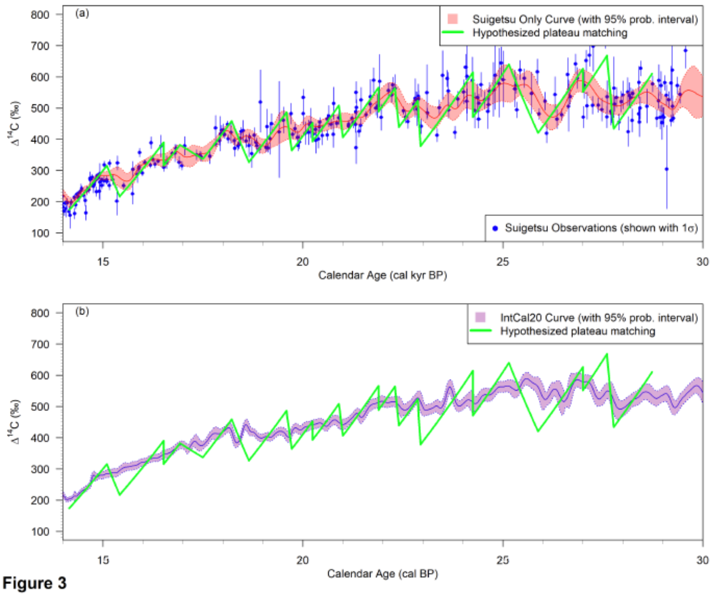


Figure 3

Fig. 3a of B&H shows the translation into the Δ^{14}C/calendar age domain of the PT suite of plateaus, defined by SA2020 on basis of Bronk Ramsey et al., 2012 in the ^{14}C-age/ calendar-age domain. The pattern of horizontal plateaus and steep jumps transforms into the green curve with sections of steeper decrease in Δ^{14}C (the former plateaus) and sections with less decrease or even an increase in Δ^{14}C (former jumps) with time going forward. The green pattern compares reasonably well with the pink Bayesian spline of the 2020 version of Suigetsu Δ^{14}C (Bronk Ramsey et al., 2020). Fig.3b shows the same for IntCal20. At >20 cal kyr BP, conversion of cal. ages of hypothesized Suigetsu plateaus to recent age estimates of Bronk Ramsey et al. (2020) will further improve the alignment.

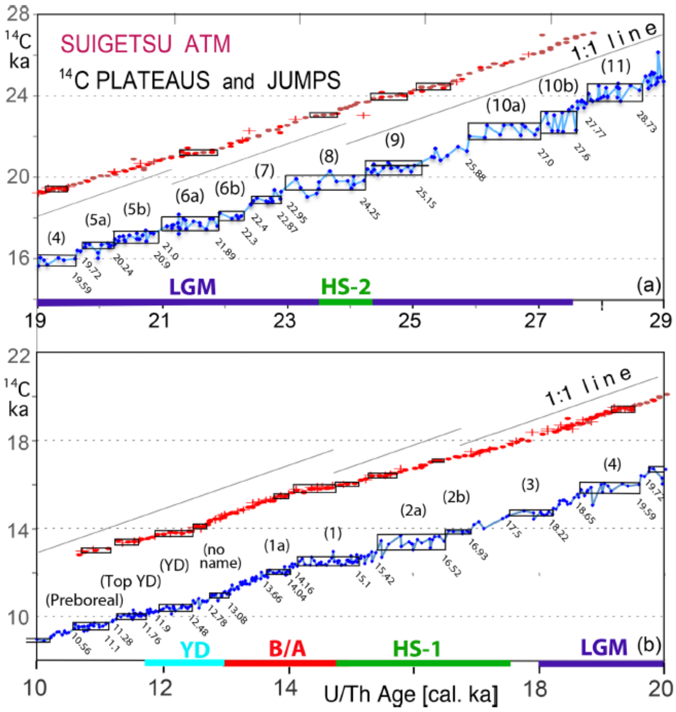


Figure 1. SA2020, shows in blue the 2012- Suigetsu ^{14}C data with plateaus >300 cal. yrs long defined for low-slope sections and, for comparison in red, the same for the Hulu record, shifted by +3000 ^{14}C yrs.

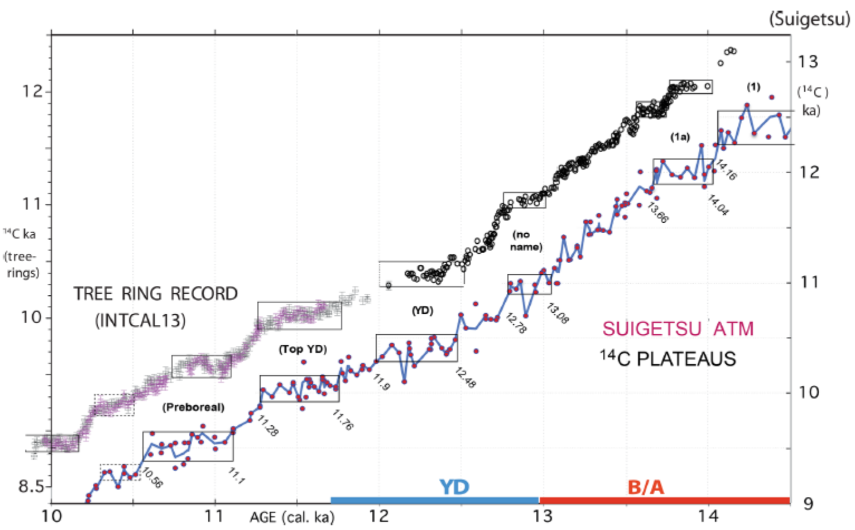


Figure 2. SA2020, shows the 2012 Suigetsu ^{14}C values (700-yr offset) and IntCal13-tree-ring values with low-slope sections >300 cal. yrs indicated by plateau bands.

2.3 This section discusses two key objections. First *'weak evidence for many of these hypothesized ^{14}C-age plateaus'* *(lines 132-133)* and second their physical impossibility *'in their model, ^{14}C ages must jump, often instantaneously, from one plateau to the next'* *(line 135)*

B&H Fig. 1–3 provide in combination with Fig.1-2 and Table 1 of SA2020 a valuable basis for the discussion of these objections. Fig. 3 shows a nice picture of fluctuating atmospheric ^{14}C concentrations, expressed as $\Delta^{14}C$ over the period 14-30 cal kyr BP, based on the primary 2020 Suigetsu ^{14}C data points of Bronk Ramsey et al., 2020, (Fig. 3a) and on the latest IntCal20 synthesis (Fig. 3b). The smoothed character of IntCal20 compared with Suigetsu is obvious. Unfortunately, B&H did not reconstruct the full record up to 10 ka, as presented in Figs. 1 by SA2020. Their more detailed Fig. 2 highlights the missing section 10 to 14 cal kyr BP, where Suigetsu and tree-ring-based IntCal 13 overlap (IntCal20 was not available yet). As can be seen, the tree ring pattern of alternating sections with more and with less slope is matched, though with significantly more scatter, by the Suigetsu data. Six 'plateaus' defined in Suigetsu match seven IntCal13 'plateaus' whereby plateau 1a of Suigetsu combines two short, close-together 'plateaus' of IntCal13. This similarity provides a basis for trusting Suigetsu as a good indicator of atmospheric ^{14}C beyond 14 cal kyr BP and, thereby, confirms the smoothed character of IntCal20 beyond the 14 kyr BP tree ring calibration (further discussion in S&G). IntCal20 provides the most reliable ^{14}C calibration we currently have, but for certain specific purposes like PT the single atmospheric Suigetsu record, although stand-alone and noisy, will be more suitable. As such our use of Suigetsu follows the encouragement in the conclusions of IntCal13.

Fig. 1 and 2 of B&H show ^{14}C age versus calendar age for Suigetsu and IntCal20 in the usual IntCal20 format. As stated by B&H in *lines 129-131* the evidence for many of the older plateaus in IntCal20 Fig. 2 is dubious. This is not unexpected considering the smoothed character of IntCal20. The following sentence '*They are not replicated in either our statistically- robust Lake Suigetsu-only curve (Fig. 1) or in the IntCal20 curve (Fig.2).'* is, however, not supported by Fig. 1. Inspecting the green plateaus, selected from the noisy Suigetsu data set by visual inspection as well as by a first-derivative kernel technique, shows that 13 of the plateaus correspond with calendar age broadening in the Bayesian-spline-generated pink band; solely plateaus 5b and 10b are not reflected in the pink band, although the local scatter of Suigetsu data makes their selection understandable. Some of the discrepancies between the 'green' Suigetsu plateau record of SA2020 and the Bayesian spline may reflect that the plateau record has not incorporated yet the recent age corrections of Bronk Ramsey et al. (2020).

B&H have spent considerable effort to document in the second section (*lines 134-145*) the physical impossibility of the PT model. They conclude that the strictly horizontal plateaus cover 82 % of the time between 14 and 29 cal kyr BP while in the jumps *'during the remaining*

18 % of the time, the radiocarbon clock was running almost 5 times too fast.' Although this sounds ridiculous and physically impossible, it is not as crazy as it seems and it points to one of the big problems in radiocarbon dating. We do not know the initial concentration of the sample/atmosphere. Since the radiocarbon-decay clock always runs at a steady pace, the varying measured radiocarbon concentrations indicate either varying sample ages or varying initial radiocarbon concentrations. B&H mention (*lines 151-155*) that during the Myake AD 774-75 event (Miyake et al., 2012) the atmospheric ^{14}C concentration increased by about 1.2 %. This provides an example of the radiocarbon 'clock' 'running' forward almost 100 years in that single year. The increase was followed by delayed decline in atmospheric ^{14}C attributed in IntCal20 to the time needed to mix the ^{14}C into the ocean which produces a saw-tooth ^{14}C concentration pattern.

The green plateau pattern of B&H Fig. 1 translated in the ^{14}C concentration domain produces a saw-tooth pattern that fits the fluctuating Suigetsu atmospheric ^{14}C concentrations in Fig. 3a reasonably well. It is, however, clear that the assumption of plateau slope zero, i.e. constant ^{14}C age with changing calendar age, is a simplifying approximation; some of the downslope sections in Fig. 3a are steeper, some less steep. Close comparison of the green curve with the pink Bayesian-spline envelope in Fig. 3a also indicates that deciding on the length of a plateau may be even more difficult than selecting its position. Mainly the statistically more uncertain section beyond ~22 cal kyr BP shows deviations with 'undershoots' for plateaus 11, 10a, and 8 while plateau 10 b is not seen in the pink band. Figures 1-3 of B&H thus demonstrate that IntCal20 is ill-suited to investigate ^{14}C fine-structure in environmental records while a Bayesian spline representation of Suigetsu preserves fine structure and yields promising results for PT studies.

2.4. B&H object that primary sediment records and their tuning to the atmosphere are not provided in the synthesis paper Sarnthein et al., 2020. The tuning is bad and results in large changes in sedimentation rates and hiatuses.

B&H complain it was *'necessary to dig into the literature to see the marine core records'* (*line 169*) and provide a list of the records they recovered. These data have been available, some as early as 2007, and it is disappointing that B&H access them only now, considering the serious objections they mention. It would have been great to have a scientific in-depth discussion earlier, preferably in the discussion phase of the synthesis paper, or earlier. Although B&H don't provide examples of their tuning objections, a major problem appears to be the fluctuating sedimentation rates that result from the introduction of multiple time markers, i.e. plateau boundaries, in the sediment records. Replacing 'constant sedimentation rates' that result from a lack of data with a pattern of significantly varying sedimentation rates can be disturbing but may also provide rewarding insights. Sedimentary and stratigraphic aspects of tuning these records are further discussed by S&G.

The reference in *lines 64-65*, and *212-224* to Umling and Thunell., 2017, using PT refers to 'puzzling results' but fails to mention the close agreement between the ages they obtained by three independent techniques, including PT, and shown in their Fig. 4. Their Fig. 3c suggests a naming problem for the youngest, 12.8-13.1 cal kyr BP, of their suite of five matched plateaus. This is the 'no name' plateau of SA2020, instead of the 'YD' plateau, which reduces the hiatus from 1200 to ~600 years. Its timing roughly corresponds to the Inter-Allerød-Cold-Period in Greenland/Northwest Europe.

Searching for the best match between the plateau suites of ^{14}C concentrations in sediment and atmosphere is a process of balancing the physics of ocean, atmosphere, and sediment by exploring different options. It has yielded surprising and sometimes controversial results, including hiatuses, and certainly warrants a critical discussion such as advocated by B&H. The collection of some twenty long records, though each individually on statistically shaky grounds, is by now providing consistent patterns indicating real past oceanic and ocean-atmosphere dynamics.

2.5. PT focus is on plateaus instead of '*matching the entire ^{14}C record with the target curve'*

This objection has the same root as 2.1 and 2.2, namely the misconception that PT correlates single plateaus, and is based on the first introductory sentence (*lines 40-41*). Thus we fully agree with B&H that the full records should be compared. The choice of a horizontal (=zero) plateau slope is simply made for the ^{14}C scatter bands with insufficient data to define a real slope. The pattern of horizontal and sloping line segments in the ^{14}C age/cal age domain facilitates visual comparison but has as a consequence that MRA values, obtained from the difference between oceanic and atmospheric ^{14}C plateaus, are constant over a plateau and change in steps from one plateau to another. In reality MRA variability will be more distributed. As made clear in the discussion of 2.3, the pattern of plateaus and steep(er) connections translates well into the saw-tooth curve of $\Delta^{14}C$ vs calendar age of Fig. 3a.

Bayesian spline fits, like shown in Fig. 3a, may offer PT another statistical method of data evaluation and a way to approximate the real slope of non-zero-slope plateaus. Approaching the real world with subtle and varying differences in slope between oceanic and atmospheric records will, however, remain a lofty goal that will require (impossibly) denser data.

2.6. B&H warn that marine age plateaus may result from slumps, sedimentation rate changes, and bioturbation around abundance maxima.

This objection has the same root as 2.1, 2.2, and 2.5. Again, the incomplete description of PT in the first introductory sentence (*lines 40-41*) is the base for admonishing SA2020, that correlating single plateaus is dangerous. Each of the processes mentioned will indeed disturb the regular age-depth pattern in a sediment core and might cause an age plateau. For this reason PT always uses a suite of plateaus so the loss or addition of a single plateau will be evident. The effect on PT of bioturbation in combination with a varying abundance of foraminifers in the sediment is discussed in our companion discussion text S&G.

2.7. Ocean modelling considerations argue against the PT results.

As already stated in the comment on *line 58* of the introduction, most of the carbon and ^{14}C reside in the deep ocean. A mass balance model of the carbon cycle thus requires that C and ^{14}C changes in the deep ocean are relatively minor and that most of the variability is located near the very surface of the ocean and in the atmosphere.

The modelling and discussion of *lines 284-336* of B&H focus on the ^{14}C concentrations of surface ocean reservoirs (*pla*) of complete ocean basins each in response to an atmospheric ^{14}C production signal. The 12-box model of Bard et al., 1997, introduced in lines 284-294, calculated the changes in ^{14}C distribution over the various reservoirs of the carbon cycle in response to a reduction of the global thermohaline circulation from today's 20 Sverdrup (Sv) to a postulated glacial 10 Sv (Fig. 4, $\Delta^{14}C$ values / $\Delta^{14}C$ in brackets). In both cases the atmosphere is the benchmark and its $\Delta^{14}C$ has been set to zero. In reality the $\Delta^{14}C$ of the 10 Sv atmosphere had increased by 35 ‰ relative to the standard atmosphere of 20 Sv.

The modelled graphs 4a,b of B&H quantify the attenuation of sinusoidal atmospheric ^{14}C signals of different frequency entering the surface ocean (4a) and a 500-year atmospheric sinusoidal signal moving down into the ocean (4b). The graphs show that the response of surface ocean ^{14}C concentration *pla* to ^{14}C concentration changes in *Atm* will be attenuated and depend on the rate of change of the atmospheric ^{14}C signal as well as on the location, here the ocean basin. B&H do not consider MRA, the difference between troposphere and surface ocean in Fig. 4b, only *pla*. For a large change in *Atm*, due to ^{14}C production or remote ocean outgassing, the calculated local change in *pla* may be small, but the change in MRA may be large and, for strong attenuation, approach in shape and size the *Atm* signal. Fig. 4 thus does not prove that large and rapid MRA signals are physically unrealistic.

The discussion of the bomb spike in *lines 318-336* is correct but provides another example of the focus on *pla* instead of MRA = (*pla-Atm*). The bomb ^{14}C signal and its penetration into the ocean have been well documented. Atmospheric $\Delta^{14}C$ values were -20‰ in 1954, +400‰ in 1962 and ~+900‰ in August 1963, all relative to the standard atmosphere. If surface ocean and atmosphere were in equilibrium in 1954 with a MRA of 400 years, then 1954 $\Delta^{14}C$ *(pla-Atm*) was -48 ‰. If *pla* did not change significantly from 1954 to 1963, then (*pla-Atm*) was -468 ‰ in 1962 and -968 ‰ in August 1963, $\Delta^{14}C$ values all based on the standard atmosphere. Converting these $\Delta^{14}C$ differences to the classical MRA: 'time needed for the atmospheric ^{14}C concentration to decay to the ^{14}C concentration of the surface ocean' that is anchor the system in the atmosphere of the time so $\Delta^{14}C_{atm}$ is per definition zero, we obtain a MRA of 3270 ^{14}C years in 1962 and one of 5720 years in August 1963. This MRA variability, following definitions, is of course the result of our bomb ^{14}C input into the atmosphere. Yet, for a Miyake event of 12‰ the *(pla-Atm*) will change by that much and MRA will increase by about 100 years over one year in a natural system.

Far more than for OGCMs, a weak point of the box model approach to probe the physical feasibility of MRA records obtained for individual sediment cores is its limited spatial resolution, limited to ocean basins. Changes in *pla* that result from local changes in ocean upwelling and mixing, as well as changes in ocean-atmosphere exchange cannot be box modelled. These changes are common, can be large and, with a well mixed, constant atmospheric ^{14}C concentration *Atm*, produce large spatio-temporal changes in MRA as further discussed by S&G.

Large changes in MRA with significant spatial variability that are revealed by PT are thus not incompatible with earth system reality as B&H claim based on the modelled results in Fig. 4. Instead, they reveal new detailed information about the interplay of ocean dynamics and the carbon cycle and provide the challenge to attribute those changes to different parts of the system and thus find out more about them.

2.8. B&H admonish that $\Delta^{14}C$ wiggles may result from production as well as from carbon cycle changes on generally centennial instead of millennial time scales.

This is a continuation of the 2.7 discussion of the effect of ^{14}C production signals on surface ocean ^{14}C concentrations. The consideration of ocean out gassing splits the problem in ocean-atmosphere of active source regions and of the passive rest of the world. For a comparison of MRA values produced via PT with model results again the focus has to be on the ocean-atmosphere difference. In the real world ^{14}C production variations and carbon cycle changes will occur simultaneously to different degrees. Separating their contributions to PT-derived MRA records remains a challenging modelling task for high-resolution OGCM that are able to incorporate local boundary conditions that cannot be considered in box models.

2.9. Sarnthein et al should have mentioned *'the two seminal papers'* regarding the use of volcanic ash layers for MRA reconstruction by Bard 1988 and Bard et al., 1994.

SA2020 give an overview of PT, its foundation, its use, and new data and insights it generated. Thus agreement between ages obtained by PT and from volcanic ashes off Chile and New Zealand was discussed. A review of the full field of MRA reconstruction, in which the Bard papers certainly would have featured, was not intended.

3/ Statistical perspective

3.1 Identifying plateaus in the ^{14}C records of atmospheric Suigetsu and ocean sediment cores is unreliable. This also applies to correlating ocean and atmosphere plateaus to obtain MRA from *pla-Atm* and ventilation ages from *Be-Atm*.

The discussion of *lines 370-385* rephrases the discussion of section 2. As already argued in 2.3 there is a decent correspondence between Suigetsu plateaus and the Bayesian spline pattern in B&H Fig. 1, also seen in the $\Delta^{14}C$ domain in Fig. 3a. This answers the first part of the objection above. The question of correlating plateaus has been the main topic of objections in section 2. The problems of correlating single plateaus were extensively discussed by B&H and their arguments are definitely valid. These problems have, however, been considered in PT. They are the reason that only a match of *full suites of plateaus* can be considered, an emphasis overlooked and not mentioned in the introductory *lines 40-41*.

3.2 This section questions the smoothed character of the Hulu record in *lines 392-422* and repeats the discussion of the real existence of atmospheric ^{14}C plateaus of section 2.3 in the statistics domain in *lines 423-454*.

B&H misrepresent SA2020, in *lines 392-399*. This may again be based on the misconception of *lines 40-41* that single plateaus are correlated instead of the full records. The Hulu record in Fig. 1 of SA2020, provides a simple graph of Suigetsu data of Bronk Ramsey et al., 2012, and Hulu data of Southon et al., 2012. Not only does Hulu show much smaller age uncertainties than Suigetsu but it also has a smoother structure. Several Suigetsu plateaus can also be seen in Hulu but quite a few cannot be identified in the smoothed record. No theory here, just facts.

B&H argue that the carbonate-based Hulu ^{14}C record experienced only limited and fairly constant smoothing and, therefore, better indicates atmospheric ^{14}C concentrations than the terrestrial macrofossil based Suigetsu, used by SA2020. The low 'dead carbon' fraction (DCF) of 480 ± 55 yr, used in IntCal20, is based on a reevaluation of the individual Hulu speleothems against the tree ring ^{14}C record for the period 10.7 to 13.9 cal kyr BP (Reimer et al., 2020). Its scatter could be the result of random scatter (null hypothesis). Since climate over this Allerød-Younger Dryas-Preboreal period was highly variable, it was concluded that Hulu DCF was insensitive to climate and could be used for the full deglacial-glacial record. The low DCF value was ascribed to the 'sandstone ceiling and open system conditions with the soil above' the section of the cave containing the speleothems (B&H *line 409*).This was recently modified to state that the original overlying limestone has been largely replaced with iron oxides (Reimer et al., 2020).

Including soil organic carbon as a potentially significant source of speleothem carbon complicates life because it will not contribute only 'dead carbon'. DCF is a calculated value indicating how much 'dead' carbon would be needed to obtain the drop in ^{14}C concentration observed in the speleothem. The speleothem carbon must have been a mixture of recent carbon from the atmosphere and root respiration, and older, not necessarily 'dead' carbon, derived from exchange with iron oxides and decomposing soil organic matter and, maybe, a remnant limestone. The soil organic carbon and iron oxides form a dynamic organic pool in continuous exchange with organic carbon transported by rain water down from the surface. This mixed carbon source makes the isotopic composition of speleothem carbon dependent on local vegetation, precipitation, and temperature influencing the balance between the different sources. The organic carbon adsorbed on iron oxides and the soil organic carbon, create an integrating memory of preceding ^{13}C and atmospheric ^{14}C concentration variability. Indications for significant centennial-to-millennial scale variations in carbon isotopic composition were found by Kong et al., 2005. Their Hulu speleothem $\delta^{13}C$ record shows short-term variations of up to 7‰, correlated with climate change as indicated by $\delta^{18}O$, over the period 10-23 cal kyr BP. As both the ^{13}C and the ^{14}C isotopic composition of Hulu speleothems will be influenced by mixing processes there is, unfortunately, no easy relationship between the two that can be used for isotopic corrections.

B&H state that the 480-yr DCF and the transport and mixing processes indicate a situation similar to the typical MRA of a low-to-mid latitude surface ocean and that some smoothing of atmospheric ^{14}C variations, as modelled in 2.7, is to be expected for the Hulu record. As discussed in 2.7, the attenuated recording of an atmospheric ^{14}C signal in the Hulu speleothem (compare B&H Fig. 4) indicates a change over time in the ^{14}C concentration difference DCF between speleothem and atmosphere in analogy to MRA = *pla-Atm* .

The second part largely repeats the objection of 2.3. As we discussed there**,** B&H fig. 1 and 3a actually show a convincing match between the Bayesian-spline generated Suigetsu curves and our selected plateaus. The argument that fluctuations in the section of IntCal20 considered could represent random scatter, i.e. the null hypothesis, can statistically not be rejected with 95 % probability. This means there is indeed no statistical proof that the observed fluctuations in the record are real. Yet, absence of statistical proof is not a statistical proof of absence. To establish the physical reality of ^{14}C 'events' statistically buried in the atmospheric and oceanic ^{14}C records we have to resort to comparing many data sets. The probability that random fluctuations will create patterns that match over a defined interval, decreases with the length of the suite of plateaus and with every new record added to the collection. By now**,** PT has employed many plateaus of considerable length and their age information and the resulting MRAs and ventilation ages provide new insights.

3.3 'How can one be sure of choosing the right plateau in a noisy world'.

This objection correctly lists how difficult it is to extract information from environmental archives. Yet, it is based on the same misconception of trying to match single plateaus, created in *lines 40-41*. The PT protocol has been developed to meet these challenges, first by matching only suites of plateaus, then by considering all lines of customary stratigraphic information and physical feasibility and by comparing alternative modes of PT and, finally, by evaluating and comparing many records.

3.4 How does one define a ^{14}C plateau.

This continues the focus on single plateaus, created by *lines 40-41*, and ignores what has been written about defining suites of plateaus in the age-depth domain and providing them with a rough time estimate using the customary stratigraphic and correlating tools. The implausible numbers presented appear to be just that, misinterpretations. No defined examples are presented.

3.5 Plateau identification by visual inspection is subjective.

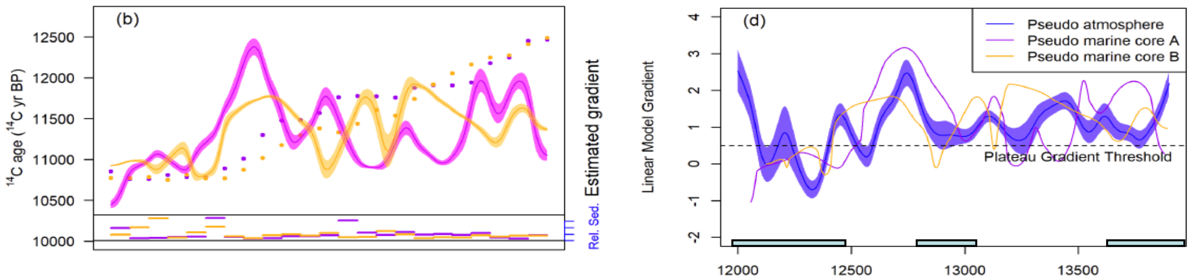
The trained eye is a wonderful instrument, yet, the argument of subjective identification is indeed correct. The use of the first-derivative-kernel- technique, developed by Mudelsee, provided a general mathematical confirmation of the subjective choices. In general, plateaus are first identified visually as ^{14}C-age/calendar-age line segments with low, near-zero slope; mathematical check and confirmation come later.

3.6 '*To asses objectively the ability to reliably identify and tune ^{14}C age plateaus*'

Plateau simulation by random scatter around a straight line. Test of pseudo-atmospheric record

This is a nice and detailed modelling test. The choice of the period 12 – 13.9 cal kyr BP, based on the use of Cariaco as example of the sediment record, is limiting because it covers only 1900 yrs and only three fairly short plateaus (Fig. 2 Sarnthein et al., 2020). A plateau match from 10 -13.9 could have used the same procedure of sampling and adding noise to the IntCal20 tree ring record for a hypothetical Cariaco record and would have been an even better test covering five plateaus instead of three. The first-derivative modelling of B&H seems to correspond reasonably well to what Mudelsee described in the supplement of Sarnthein et al., 2015. There also the source code used has been given. Mudelsee states he used a modest undersmoothing to bring out details but aimed for a minimum plateau length of 300 yr. B&H appear to smooth less and obtain mini plateaus that we rejected as too uncertain on the basis of our sampling resolution. The choice of a gradient of 1, that is one ^{14}C

year per calendar year instead of 0.5 seems better as it approaches natural ^{14}C decay and the IntCal curve for this time interval. However, this choice should not change the results; just make them more difficult to read in the figures. B&H Fig. 5a-d demonstrates that noise can indeed change our realization of the underlying record and, consequently, modify a first derivative plot. Yet, the three plateaus, selected in Suigetsu and IntCal13 tree rings of Fig. 2 in Sarnthein et al., 2020, can still be seen as major structures. The test of B&H would have been easier to judge if the three plateaus had been indicated for comparison on the X-axis of Fig. 5.



B&H Fig. 6. In 6b pseudo-marine ^{14}C records A (purple dots) and B (yellow dots) with first derivatives on depth scale. In 6d first derivatives of sediment record A and B (purple and yellow) and of matching atmospheric record on calendar age scale. In blue on X-axis the plateaus of the underlying tree ring record.

3.7 Plateau simulation by random scatter around a straight line: Test of pseudo-marine record.

Like 3.6 this exercise may promise to 'realistically scramble' the atmospheric ^{14}C record in such a way as it might be preserved in a 'nice' sediment core like Cariaco. The crucial record to study is Fig.6b. B&H (*line 631-641)* start a visual description of the pseudo sediment ^{14}C data and identify observations #1-5 in pseudo 'core A' as potential 'plateau' (*lines 632-635*). They don't identify anything else so, logically, the conclusion of their exercise is that there can be no reliable identification.

If we continue the B&H discussion of Fig. 6b above, then pseudo-core A and B both show nearly constant ^{14}C ages, a plateau, for observation points #1-6 (=pink and yellow dots) , with B extending back to #7. Then ^{14}C ages increase till observation #10 in A, #11 in B, and show little change for observations #11 through #16 (A) or #17 (B) which indicates a potential second plateau. Beyond that we have an irregular increase of ^{14}C ages. If we transfer these choices in Fig. 6b to a time scale in 6c and 6d, it is clear that not only the 12-12.5 cal kyr BP

'YD' plateau could be identified in pseudo-cores A and B but that also the presence of the 'no name' plateau at 12.8-13.1 was seen in both. The third plateau is not reflected. The first derivative has low values where a group of ^{14}C-age data points has similar values. This works for the 12-12.5 plateau. The 12.8-13.1 plateau shows some scatter in ^{14}C ages and, accordingly, the first derivative fluctuates but still gives some low values. The fluctuations of the first derivative indicate it reacts to individual data points, which indicates the kernel is undersmoothing. Having the 'estimated gradient' Y-axis in 6c and 6d, like in Fig. 5, and the three plateaus from Sarnthein et al., 2020, indicated on the X-axis in Fig. 6a-c would facilitate the comparison.

As B&H state in the discussion of this experiment, they tried to mimic the plateau tuning of the papers by Sarnthein et al. Yet, the details of the kernel set-up determine the smoothing and their kernel optimization may have been slightly different. If one compares the pseudo planktic record with the pseudo atmosphere in Fig. 6d, the 12-12.5 and 12.8-13.1 plateaus have been identified in this statistical exercise. Accordingly, the underlying structure ('plateaus') of the IntCal tree ring record indeed was detected. The conclusion in B&H *lines 644-650* is thus incorrect, while not supported by their Fig. 6. On the contrary**,** Fig. 6 shows that even in a short segment with only three plateaus two out of three features of the underlying fine structure can be recovered and correlated The modelling exercise also illustrates that, 'even under favourable conditions', it is a difficult task to extract low-amplitude signals from a noisy record. In real records of planktic ^{14}C that have been subjected to sediment disturbance and potential changes in ocean mixing, the fine structure extracted from each individual record must be checked on its physical feasibility. It is clear that long suites of plateaus, such as used in PT, need to be matched with the atmosphere and with other similar records before they can be accepted. Since the beginning in 2007 many records have been obtained that give a growing confidence that PT provides a means for extracting new information regarding the variations in internal ocean dynamics and ocean-atmosphere exchange over last glacial-deglacial-Holocene times from open ocean sites otherwise lacking clear chronostratigraphic markers for detailed age control.

3.8 Contention that *'Lake Suigetsu alone provides a more precise reconstruction of atmospheric ^{14}C levels from 55-13.9 cal kyr BP than IntCal20 synthesis*'.

This section provides a beautifully clear description of what IntCal20 is (and is not) in defence against an attack that never took place. The smoothed character of IntCal beyond tree ring calibration has long been recognized. With the new Bayesian-spline approach IntCal 20 is a lot less smooth than its predecessor IntCal13. Also, the introduction of a modelled time varying reservoir age correction for the different marine records has been a big step forward. Yet, the current IntCal 20 version is the best choice we have for ^{14}C calibration but it is a work in progress and still has a smoothed character.

As stated in the conclusions of IntCal13: '*We encourage researchers to use the available data to synthesize curves in their own way and potentially contribute new and improved strategies to the construction of the ^{14}C calibration curve.*' To explore the ^{14}C fine structure of the ocean sediment record you need the best-available atmospheric fine structure as global benchmark. PT therefore uses the Suigetsu sediment record, based on purely terrestrial macrofossils, as atmospheric benchmark instead of the allegedly more secure but also smoothed IntCal20, resulting from a statistically sound synthesis of all available data sets. The objection that Suigetsu is only one record and maybe noisy is correct but fades against the fact that Suigetsu directly represents the atmosphere. PT follows the encouragement of IntCal13, quoted above, and uses the Suigetsu record as a research tool to extract new information from the marine records that can, we hope, contribute to the next, improved version of IntCalXX.

References

Bard, E., Raisbeck, G., Yiou, F., Jouzel, J. Solar modulation of cosmogenic nuclide production over the last millennium: comparison between ^{14}C and ^{10}Be records. *Earth and Planetary Science Letters* 150, 453-462. doi: 10.1016/S0012-821X(97)00082-4, 1997

Bronk Ramsey. C., Heaton, T.J., Schlolaut, G., Staff, R.A., Bryant, C.L., Brauer, A., Lamb, H.F., Marshall, M.H., Nakagawa, T. Reanalysis of the atmospheric radiocarbon calibration record from Lake Suigetsu, Japan. *Radiocarbon* 62, 989-999, doi: 10.1017/RDC.2020.18, 2020.

Bronk Ramsey, C., Staff, R..A., Bryant, C.L., Brock, F., Kitagawa, H., van der Plicht, J., Schlolaut, G., Marshall, M.H., Brauer, A., Lamb, H.F., Payne, R.L., Tarasov, P.E., Haraguchi, T., Gotanda, K., Yonenobu, H., Yokoyama, Y., Tada, R., Nakagawa, T., A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr BP. *Science* 338: 370-374, 2012.

Kong, X., Wang, Y., Wu, J., Cheng, H., Edwards, R.L., and Wang, X., Complicated responses of stalagmite $\delta^{13}C$ to climate change during the last glaciation from Hulu Cave, Nanjing, China, *Science in China Ser. D Earth Sciences*, 48, (12), 2174-2181, 2005.

Lohman, G., Butzin, M., Eissner, N., Shi, X., Stepanek, C., Abrupt climate and weather changes across time scales. *Paleoceanography and Paleoclimatology*, submitted 2021

Miyake, F., Nagaya, K., Masuda, K., Nakamura, T., A signature of cosmic-ray increase in AD 774-775 from tree rings in Japan. *Nature* 486, 240-242, doi: 10.1038/nature11123, 2012

Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg., A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, H., Reimer, R.W., Richards, D., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S., Fogtmann-Schulz, A., Friedrich, R., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Minuro Sakamoto, M., Sookdeo, A., Talamo, S., The IntCal20 Northern Hemisphere radiocarbon calibration curve (0-55 kcalBP). *Radiocarbon* 62, 724-757, doi: 10.1017/RDC.2020.41. 2020

Sarnthein, M., Balmer, S., Grootes, P.M., and Mudelsee, M., Planktic and benthic ^{14}C reservoir ages for three ocean basins, calibrated by a suite of ^{14}C plateaus in the glacial-to-deglacial Suigetsu atmospheric ^{14}C record, *Radiocarbon*, 57, 129-151, doi: 10.2458/azu_rc.57.17916, 2015

Sarnthein, M., Grootes, P.M., Kennett, J.P., Nadeau, M.J., ^{14}C Reservoir ages show deglacial changes in ocean currents. In: Ocean Circulation: Mechanisms and Impacts, *Geophysical Monograph Series* 173, edited by: Schmittner, A., Chiang, J., and Hemming, S., American Geophysical Union, Washington, DC. 175-179. doi: 10.1029/173GMOX, 2007.

Siegenthaler, U., Heimann, M., and Oeschger, H., ^{14}C variations caused by changes in the global carbon cycle. *Radiocarbon* 22, 177-191, 1980.

Southon, J., Noronha, A.L., Cheng, H., Edwards, R.L., and Wang, Y., A high-resolution record of atmospheric ^{14}C based on Hulu Cave speleothem H82, *Quaternary Science Reviews*, 33, 32-41, 2012.

Umling, N.E. and Thunell, R.C., Synchronous deglacial thermcline and deep-water ventilation in the eastern equatorial Pacific. *Nat. Commun*. 8. 14203 doi: 10.1038/ncomms 14203 , 2017